The photocurrent of resonant tunneling diode controlled by the charging effects of quantum dots

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Abstract

We experimentally studied the photocurrent of AlAs/GaAs/AlAs double barrier resonant tunneling diode (RTD), which is composed of an InAs layer of self-assembled quantum-dots (QDs) on top of the AlAs barrier layer. It is found that the charging InAs quantum dots can effectively modulate the carrier transport properties of the RTD. Moreover, we also found that the resonant tunneling current through a single energy level of an individual quantum dot is extremely sensitive to the photo-excited holes bound nearby the dot, and the presence of the holes lowers the electrostatic energy of the quantum dot state. In addition, it is also observed that the photocurrent can increase step by step with the individual photon pulse excitation when the illumination is low enough. The experiment results well demonstrated the quantum amplified characteristics of the device.

I. INTRODUCTION

Recently, QD based single photon detectors have attracted increasing attention mainly due to their single photon sensitivity and photon number resolving capability. It has been demonstrated that both field-effect transistor [1] and resonant tunneling diodes (RTD) [2, 3] modified which contains a layer of QD layer can detect single photons at temperature of 4.2K. The concept of RTD was first proposed by Tsu and Easki in 1973 [4]. In 2005, Blakesly first introduced the quantum dot concept into the conventional RTD. The experiment results showed that a single photon can be efficiently detected in the device. Physically speaking, when the RTD layers have the appropriate alignment voltage, a current can tunnel resonantly through the double barrier structure. It is indicated that the effective multiplication factor is in the order of 10^8. The very high multiplication factor is caused by the photo-excited holes being stored in the QD close to the RTD structure [5-8]. In this paper, we have investigated the photocurrent of AlAs/GaAs/AlAs double barrier resonant tunneling diode. It has been indicated how the photocurrent is influenced by the charging and discharging of the InAs dots. The Photo-excited holes reduce the negative charge in the dots, and thus lower the electrostatic energy of the tunneling channel of the active quantum dot. It is also found that the photocurrent increases in step-like style with a laser pulse coming when the applied bias is fixed as constants.

II. DEVICE STRUCTURE

The structure was grown by molecular beam epitaxy on a (100) semi-insulating GaAs substrate. The detailed device structure is shown in Fig.1.

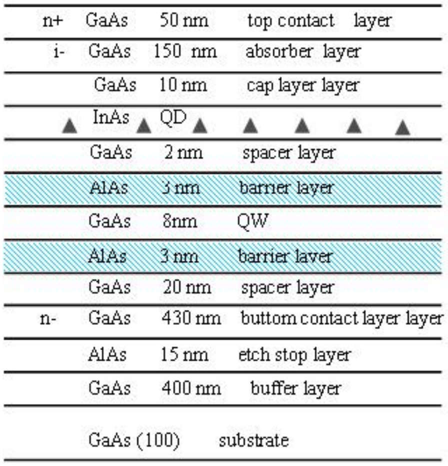

Fig. 1 Double barrier RTD structure with InAs dots being buried in the cathode side.

The fabricating progress contains three steps, that is the same as reference [7, 8]

III. RESULT AND DISCUSSION

Figure 2 shows the current-voltage (*I-V*) characteristics measured at 77K in the dark and under illumination by using laser light of wavelength $\lambda = 650nm$. There is a distinct difference in the resonant tunneling peaks at negative and positive collector-emitter voltages. It can be seen that the peak of the characteristic corresponds to the resonant tunneling through the double barrier structure for both forward and reverse biases. For reverse bias, we can find the explanation in reference [7]. Therefore, here we only discuss the case of forward bias. Notice that there is only light response at the voltage between 0.75V and 1.56V. When the voltage is greater than 1.5V, the device works in negative differential resistance region, and there is no light response.

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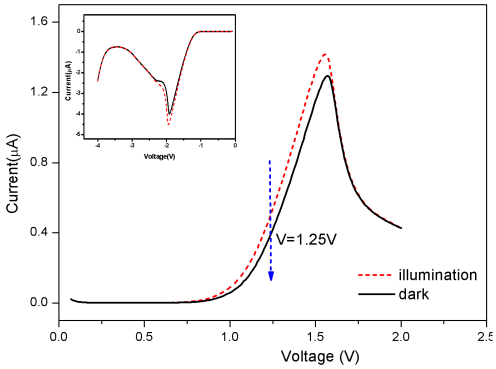

Fig.2 I-V curve at T=77K in the dark and under illumination with laser light ($\lambda = 650nm$). Under illumination the light response locates in the positive resistance region. Inset shows the light response with the reverse bias.

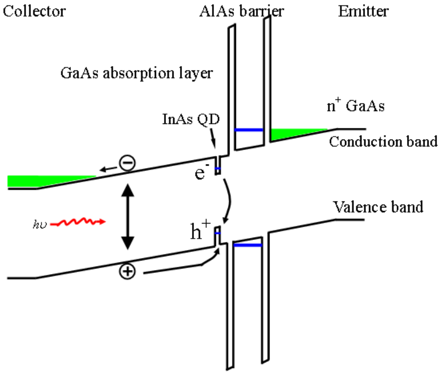

Fig.3 (a) Schematic band diagram of AlAs barrier QDRTD detector grown on a GaAs substrate shows the charge separation of photogenerated carriers in the absorption layer. The Photo-excited holes are attracted to the QDs and then are recombined with the electrons trapped inside.

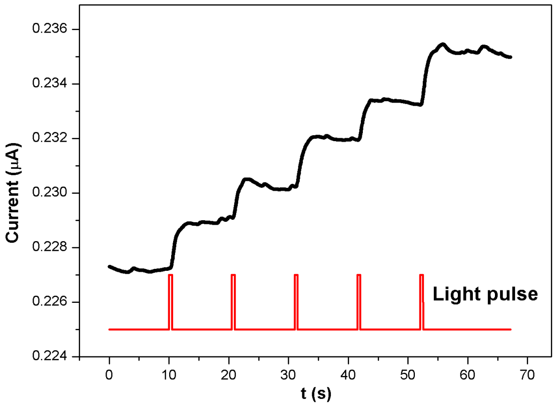

Fig. 3 (b) Time dependence of the tunnel current at V=1.25V with the excitation of laser pulse.

For conventional resonant tunneling diode, when the resonant energies between the double barriers approach the Fermi energy of the electrons at the emitter contact, the current maxima occurs. But here, the quantum dot layer in the structure has an important effect on the current-voltage characteristic of the QDRTD. The energy band diagram of the structure in forward bias is shown in Fig. 3(a). The response of the tunneling current to illumination is further illustrated in Fig. 3(b). Here we set the applied bias at V=1.25V, which is well below the resonant peak of I-V curve in the dark background. Since the conduction band level in the quantum dots has a lower energy than that in GaAs, therefore, each dot traps several excess electrons at the initial. For forward biased QDRTD with the light illumination, the photo-excited electrons are collected by the top contact, and the photo-excited holes are drifted to the InAs dot layer. Then the holes are captured by the QDs according to the external electrical field direction. When a quantum dot is depleted with a single photo-excited charge, the band bending can shift the energy levels further towards the resonance and cause the increase of the tunneling current. As shown in Fig.3(b), when a light pulse is incident, more holes can be captured by dots. As long as the life of holes is long enough, the current can keep the same value. When the next pulse comes, the current can increase step by step.

IV. CONCLUSION

In conclusion, we have indicated the photon detection based on a AlAs/GaAs/AlAs resonant tunneling diode containing a layer of InAs quantum dots. The Photo-excited holes reduce the negative charge in the dots, and thus lower the electrostatic energy of the tunneling channel of the active quantum dot. For a fixed applied bias, the photocurrent increases in step-like style with a laser pulse coming.

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